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Combustion of Biomass Fuel and Residues: Emissions Production Perspective

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Additional information is available at the end of the chapter

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Abstract

This article provides possibilities for minimising the emissions from eight types of biomass combustion boilers given by virtue of continuous emission measurement. The measurements were carried out on various types of one- or two-stage combustion devices. In all investigated modes of combustor operation, the concentration of nitrogen oxides in the whole cycle of fuel combustion was without marked deviations and far lower than the emission limit of 650 mg/mn³. Concentrations of carbon monoxide (CO) and total organic carbon (TOC) are extremely variable at some operating schedules of combustion boilers. The variability of these concentrations indicates that there are unstable aerodynamic conditions in the combustion device. The causes of this aerodynamic instability have been studied. The mode with stable aerodynamic conditions, for which emission concentrations of CO and TOC are relatively stable, has been determined.

Keywords: biomass, residues, combustion, emission, measurement

1. Introduction

The combustion plants, especially for the wood fuel, wood residues and other biomass combustion, are often located near residential homes and therefore they are under a direct visual control of the inhabitants. The plants take an interest in reducing their negative impact or negative impression (of the black smoke) of the inhabitants without a more distinct investment.

Wood represents one of the oldest materials used for heat and energy generation via direct or indirect burning. As fuel, wood can be evaluated similarly to any other solid fuel in accordance with the following criteria:

1. chemical composition
2. combustion heat and calorific value
3. volatile matter content
4. ash content

The chemistry of wood combustion is a complex process. In a flame, there are many thermo-degradation and oxidation reactions accompanied by the formation and interactions of radicals. However, as a result of these reactions, in the flue gas created during the wood combustion not only carbon monoxide (CO) and NO_x are present but also some other dangerous substances: CO_2 , H_2O , N_2 , and unreacted surplus O_2 . Moreover, in the imperfect oxidation of volatile matter products in the combustion chamber, the flue gas of wood contains different hydrocarbons, which concentration can be—from the point of view of the emission standards—expressed as total organic carbon (TOC). Wood contains more hydrogen than any other fuel which is the reason why significantly more hydrocarbons are created during its combustion. For this reason, the problem of hydrocarbon emissions from combustion can be considered to a certain degree as a specific problem related to the wood combustion process.

Other harmful substances, such as, for example, polycyclic aromatic hydrocarbons (PAU), are not represented in wood structure. Their presence in flue gases is clear evidence of synthetic reactions in a flame. The original loosely connected cyclic hydrocarbons of wood are loosened in a flame and they condense at higher temperatures. In different furnaces, these PAU can reach a significant ratio from the total hydrocarbon emissions in flue gas [1]. Combustion of wooden waste with chlorine is a particularly serious problem. Such waste comprises residues of chipwood boards on a urea–formaldehyde (UF) resin basis with a NH_4Cl catalyser as well as surface materials (polyvinyl chloride, PVC). The aforementioned catalyser until recently was almost the only hardener of UF resins used. In 1 kg of particle board is there from 1 to 3.5 g of Cl. Theoretical calculation leads to chlorine concentration values (or HCl, resp. Cl^-) in flue gas from 100 to 400 mg/m^3 [2]. These concentrations significantly exceed present emission limits.

Fuels with the compound ratio of phenol character and chlorine are the reason for a high probability of dioxin formation. Theoretically, a very low concentration of chlorine in fuel is sufficient for the formation of a trace concentration (in ng/m^3) of these toxins. Possible ways of such formation are suggested by [3].

In order to monitor the quality, optimisation and regulation of the wood combustion process, the most advantageous way is to use the measurement of CO and NO_x concentrations and the O_2 content in flue gases [4].

The quality of wood and wood waste combustion in an enclosed combustion chamber depends on the water content and chemical composition of the wood itself and on combustion parameters. Combustion parameters of particular importance include:

- temperature in the combustion chamber,
- manner in which the individual phases of burning are separated,

- the surplus of air and its distribution into primary, secondary and even tertiary combustion processes,
- the thoroughness with which flammable gas mixes with air, and
- time (retaining period) during which flammable gas components are mixed with oxygen at the required reaction temperature (homogeneous oxidation).

The impact of the above-mentioned factors influencing the combustion quality and the harmful substances formation is detailed in **Figure 1**.

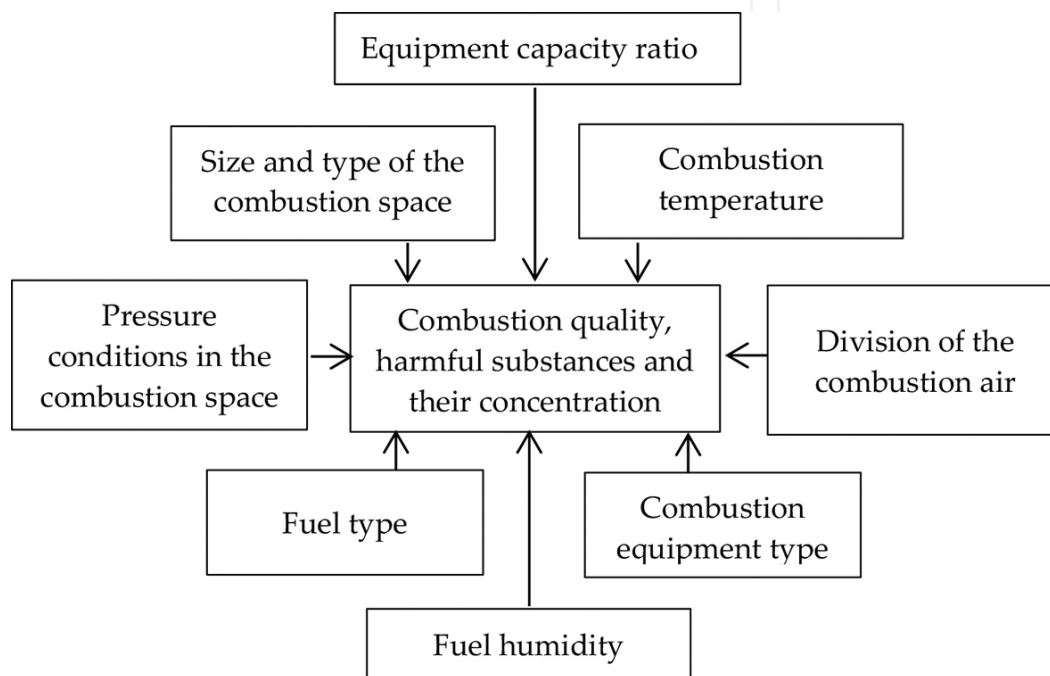


Figure 1. Impact of the factors influencing the combustion quality and the harmful substances formation (ratio of the equipment capacity in relation to the nominal capacity).

For energy generation from wood and wooden waste, different types of combustion equipment are used, which can be divided into:

- single stage
- two stage.

Single-stage combustion equipment can be characterised by one common space for the thermal decomposition and combustion of formed gaseous flammable products. According to the construction and characteristics of the burned wood, they can be divided into the combustion equipment for:

1. combustion of dry wood with humidity of $W < 30\%$, the most suitable here is grate combustion equipment;

2. combustion of wet wood with humidity of $W > 30\%$, where combustion equipment with lower fuel supply and fluid ones are mostly used.

Two-stage combustion plants burning wood and wood waste comprise a preheating firebox (first stage) and secondary combustion chamber (second stage). The wood is partially broken down by pyrolysis and gasification in the preheating firebox through oxidation. In the second stage, the gaseous products from the first stage (primarily carbon monoxide and hydrocarbons) are burned with an appropriate surplus of air. The two-stage combustion equipment is mostly suitable for combustion of dry ($W < 30\%$) pieces of wood and wooden waste or wood chips.

Experimental combustion tests are highly important for boiler operation regulation optimisation and accomplishment of the lowest emissions possible from wood and waste [5, 6]. Practical boiler regulation is varied from manual to various levels of automation and sophisticated solutions [7]. The boiler regulation demands operation optimisation and also regulation from the viewpoint of emissions [8].

From the viewpoint of minimising emissions, the request for correct biomass and varied wood waste (postconsumer wood, medium fibreboard (MDF) bound by UF resin, particleboards bound by UF resin, particleboards bound by UF resin with lamination coating on the basis of melamine-urea-formaldehyde resin) in boiler operation is particularly characteristic. Values of contaminating substance concentrations in waste gases are influenced not only by combustion technique, fuel humidity and calorific value of fuel but also by the method of fuel feeding, its dimensions, composition, etc. [9, 10]. One problem in minimising emissions is also the high percentage of volatile combustibles in biomass. In fact, there is no universal wood combustion device that can be used for every kind of biomass. Wood-based waste processing materials that have been processed with different types of adhesives, coatings and preservatives are extremely difficult to recycle as a raw material [11]. The authors of the work [12] spring harvested corn stover used for direct combustion in a 146-kW dual chamber boiler designed for wood logs. Combustion trials were conducted with corn stover and wheat straw round bales in a 176-kW boiler [13].

New combustion plants generating electricity from biomass must comply with best available techniques (BAT) requirements. Detailed knowledge of the impact of combustion parameters on the formation of emissions is critical when developing such plants and in efforts to achieve additional reductions in emissions from existing plants. Emissions are minimised over the long term by using the lessons learned from monitoring emissions across a broad range of combustion plants fuelled by various types of biomass. This chapter is focused on resolving problems related to minimising emissions from the combustion of biomass.

The aim of this chapter is to analyse the process of the biomass fuel and residues combustion and the emission production on the basis of emission measurements during the model combustion testing, and to propose solutions for minimising the emission of the investigated combustion plants.

After preliminary evaluation of the structural design of the combustion plant and analyses of the biomass fuel or residues, it was decided to analyse in detail the process of combustion on

the observed combustion plants. On the basis of proper measurements and in the context of the theoretical and practical knowledge of the combustion, we will:

- analyse the time behaviour for emissions from four types of wood boilers,
- specify the causes of the negative influences of operating the combustion plant on polluting the atmosphere,
- evaluate the possibilities for reducing emissions on the basis of time behaviour hereof and propose in what ways and means (the proposal of alternative solutions) it would be possible to co-ordinate outputs of the sources of the air pollution with the requirements of the Air Quality Act and belonging regulations,
- modify the usual mode of boiler operation, so that considerable reduction of ambient air burden by emissions is achieved,
- define how as much as possible to reduce the impact of the plant on the neighbouring residential area with respect to the requirement of the reasonable expenses for the implementation.

2. Experimental

The results of producing the pollutants were achieved in the different combustion plants of low and medium capacity when burning various kinds of biomass fuel or residues. The generalisation of the results will be realised on the basis of comparing the experimental results with the results of producing the pollutants in the standard wood combustion plants.

2.1. Materials

Cuttings of dry native wood, other biomass and waste from fibreboards, particleboards and other wood materials were used as fuel. The kind of combusted biomass fuel and residues during the emission experiments in combustion plants:

- residues of a Sorghum biocolor var saccharatum (L.) Mohlenber,
- residues of dry native wood with lengths up to 0.75 m,
- residues of beech and pine lumber, and cuttings after drying,
- large-surface residues of medium fibreboards (MDFs) bound by the UF resin,
- large-surface material (waste of particleboards bound by the UF resin) with lamination coating on the basis of melamine-urea-formaldehyde resin (two sorts),
- large-surface residues of particleboard bound by the UF resin with lamination coating on the basis of the melamine-urea-formaldehyde resin,
- residues of plywood bound by the UF resin,

- crushed briquettes produced from a mixture of waste from particleboards (90%) and natural wood (10%),
- the two-stage combustion equipment for wood and wood waste combustion comprise a pre-furnace chamber, where the wood pyrolyses/gasifies by partial oxidation; subsequently, in the second phase the gaseous products and the carbon monoxide are burned with the respective air surplus for gaseous fuel. The two-stage combustion equipment is mostly suitable for combustion of dry ($W < 30\%$) pieces of wood and wooden waste or wood chips.

2.2. Methods

Boilers with discontinuous and continuous feeding were monitored. The broader characteristic of these boilers will be described in this chapter.

There were eight types of boilers used as the subject of research interest:

Boiler 1: a boiler with a stationary horizontal grate with thermal input of approximately 200 kW for heat production for a small manufactory shop. The remains of a *Sorghum biocolor var. saccharatum* (L.) Mohlenber shrub had originally been burnt in the boiler. Black smoke and unmeasurably high concentrations of CO and total organic carbon (TOC) emissions led to a boiler shutdown. An effort was made to keep this shop in a marginal zone and to verify the possibility of using another type of fuel with the aim of reducing emissions. An experiment with combustion of native wood briquettes was realised. During the experiment, manual briquette feeding was realised once per 60 min.

Boiler 2: a gasifying boiler with a nominal output of 99 kW for combustion of piece rests of dry native wood residues with lengths up to 0.75 m from furniture production. Feeding of fuel to the boiler was performed manually. The normal operator's dosage period was 40–60 min.

Boiler 3: a two-stage combustion boiler with manual regulation of primary air. The original nominal output of the grate boiler was 3.3 t/h of steam with a nominal temperature of 173°C and operational pressure of 0.75 MPa (2.5 MW). Firewood with a maximum consumption of 500 kg/h was the original nominal fuel capacity of boilers. The original boiler was adapted in such a way that a primary combustion chamber was added to it and the original combustion chamber served as a secondary combustion chamber. Types of firewood and waste wood were as follows:

- Beech and pine waste lumber, and cuttings after drying;
- Large-surface waste of medium fibreboard bound by UF resin;
- Large-surface waste of particleboards bound by UF resin;
- Large-surface material (waste of particleboards bound by the UF resin) with lamination coating on the basis of melamine-urea-formaldehyde resin.

Boiler 4: an automated warm-water boiler for waste wood combustion with a thermal input of 318.6 kW. Crushed briquettes produced from a mixture of waste from particle boards (90%) and natural wood (10%) production were combusted in the warm-water boiler. Particle boards

were produced on the basis of urea–formaldehyde resins or phenol–formaldehyde resins and were laminated with melamine resin and ABS foil. Edge-forming bands of polyvinyl chloride (PVC) were not used.

Boiler 5: a two-stage combustion boiler with capacity of 0.6 MW. In the pre-furnace chamber, the dosed fuel comes to a slope grid where it is pre-dried. Subsequently, the fuel falls to a horizontal grate where it is gasified by the substoichiometric content of primary oxygen. The flammable gases formed burn out after mixing with the secondary air in the afterburning chamber under the boiler. Dosing of the fuel into the boiler can be automated or manual, therefore it is ideal for studying the operation modes.

Boiler 6: a two-stage combustion boiler with capacity of 4.1 MW with partial recirculation of flue gas. In the primary combustion chamber, there is a slope grate under which the strictly regulated primary combustion air is driven. Secondary combustion air and recirculated flue gas are driven to the entrance to the secondary combustion chamber. The boiler power and the addition of the combustion air are automatically regulated by variators on the basis of measurement of actual thermal parameters in different points of the combustion chambers and pressure.

Boilers 7 (MA 23) and 8 (PU 25) for case study: The object of power, emission and safety operational testing was hot water boiler MA 23 for gasification of wood logs with nominal heat output of 23 kW (**Figure 2(a)**), and hot water boiler PU 25 with automatic feed fuel with nominal output of 23 kW (**Figure 2(b)**).

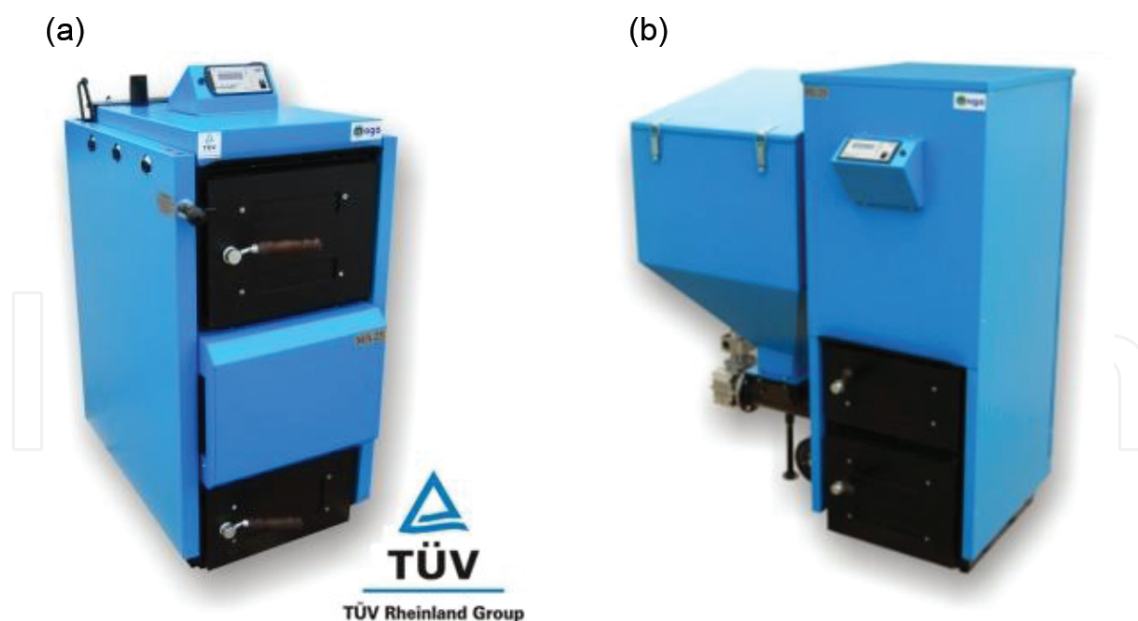


Figure 2 (a) Gasification boiler MA 23 and (b) automatic boiler PU 25.

The boilers are equipped with electronic temperature controller and a temperature safety fuse. Condition of the boiler and of its accessories was tested in accordance with the standardly supplied technical documentation. During testing, the influence of the conditions of fuel

combustion on emissions was experimentally verified, as well as resistance to thermal overloading of the boiler and of equipment for removal of excess heat. Spruce wood with a moisture content of 10% and a calorific value of 15,266 MJ/kg was used as a test fuel, and for the boiler 25 PU we used pellets with a calorific value of 16.5 MJ/kg [14–17].

2.3. Emission measurements during the wood waste combustion

Measurement of gas emissions was executed in line with standards (STN EN 15058:2007; STN EN 14789:2006; STN EN 12619:2013; STN ISO 7935:1992).

CO, NO_x and O₂ concentrations were quasicontinual measured with automatic analyser of furnace gases—ECOM SG-Plus from the RBR COMPUTERTECHNIK (Germany) on electrochemical principle and continuously measured with a HORIBA Enda 600 and Pg analyser (Japan), acting on the physical principle of non-dispersive infrared (NDIR) spectroscopy.

Organic substance emissions expressed as total organic carbon (TOC) were continuously measured with a BERNATH ATOMIC analyser (Germany), acting on the principle of flame ionization detector (FID) and ThermoFid analyser.

Calibration gases were delivered came from the delivery of the Linde Gas k.s. Slovakia.

Solid pollutant emissions were measured using a gravimetric method after a representative isokinetic sample was taken in accordance with STN EN 13284-1. Before the representative sampling process, at the measuring point, a speed profile of the air mass was measured in the piping using a Prandtl tube. The representative sample taking process at the measuring point was executed at several measuring points of the piping cross section. The measuring points were selected in order to ensure an objective sample taking from the whole piping cross section.

Smoke darkness measurements were conducted according to opacity in the Bacharach scale with a BRIGON company appliance (Germany).

3. Results and discussion

Model combustion testing and measurements of emissions have analysed the process of production of pollutants in the process of biomass fuel and residues combustion. The particularities of various kinds of biomass manifest themselves also through various thermochemical characteristics, affecting the combustion and pyrolysis processes [18, 19]. Many combustion devices are manually regulated and/or do not have regulation of biomass combustion parameters in combination with emission values of contaminating substances (°C, concentrations of CO₂, C_{CO}, C_{TOC} and C_{NOx}). The knowledge of biomass—combustion technique—combustion conditions—emissions interactions is an essential prerequisite in these cases for minimising emissions from manually regulated combustion devices.

When combusting the remains of a *Sorghum biocolor var. saccharatum* (L.) Mohlenber shrub in boiler 1 with a stationary horizontal grate, we were searching for the causes of low-quality burning. The remains of the shrub were thin and burned quite rapidly. As a consequence of

large burning velocity, no complete oxidation of burning products took place. We supposed for this reason that the CO and TOC emissions were above the measurement ranges of analysers ($\approx 10,000$ ppm). We have not yet encountered a similar case in professional sources. Recognition of the causes of high concentrations of CO and TOC in flue gases enables the identification of solutions to minimise emissions from small boilers that currently are a long way off from the state of the art.

A reduction of burning velocity can be achieved through addition of native wood briquettes. Native wood briquettes have a high density (approximately 1.1 kg/dm^3) that is incomparably higher than the density of the shrub (approximately 0.29 kg/dm^3). When combusting native wood briquettes in this boiler, a marked reduction in black smoke and gaseous contaminating substances (**Figure 3**) was achieved. At smaller differences in the biomass density, such marked differences probably would not have become evident. Results from the combination of thermogravimetric and differential thermal analysis (TG/TGA) of six species of wood show that there is no connection between the wood density and the parameters characterising the burning process [20].

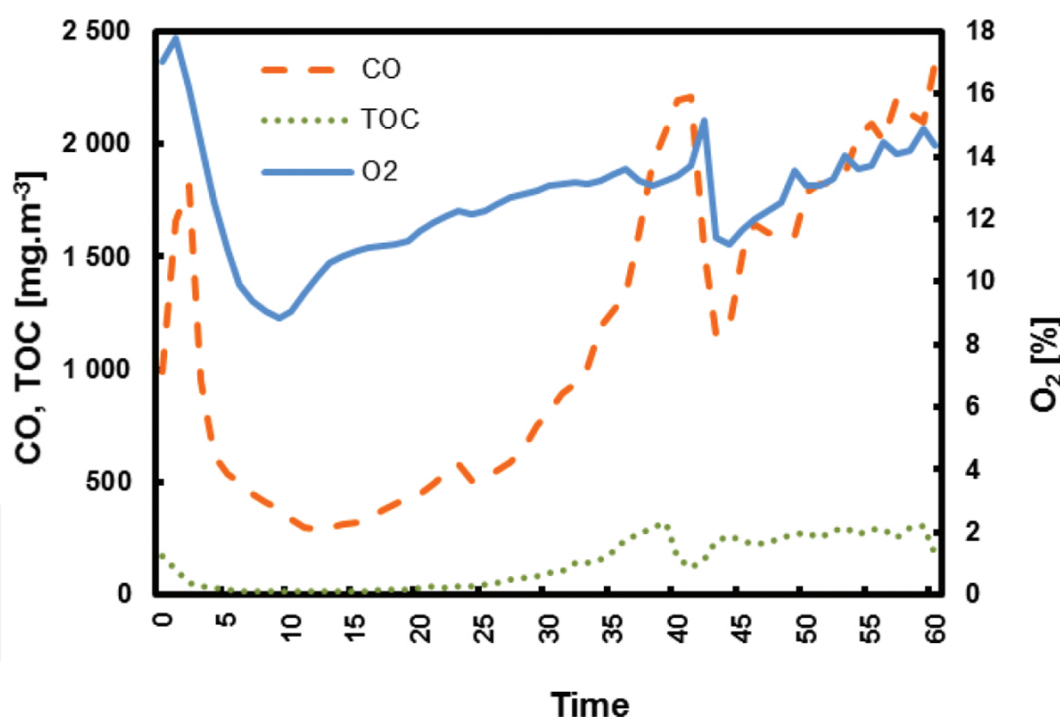


Figure 3. Trend in the emissions of CO, TOC and O₂ during combustion of wood briquettes.

The time behaviour of contaminating substance emissions (in recalculation to reference oxygen, 11% O₂) was monitored within the whole interval, starting with fuel feeding. Mean values of CO, NO_x, TOC and O₂ concentrations were recorded in 1-min intervals. The time behaviour of smoke darkness was monitored in 5-min intervals.

Measuring points were located in a vertical duct system behind a waste gas fan.

It can be seen that after briquette feeding, the CO concentration increases sharply. Then, a stable phase of briquette burning sets in at oxygen contents in waste gases of approximately 9–13%. An emission extreme at a burning time of 35–40 min can indicate unstable aerodynamic conditions in the furnace, for example, collapse of a uniform fuel layer in the furnace. Morissette et al. [13] measured average emissions of CO, NO_x and SO₂ for burning corn stover 2725, 9.8 and 2.1 mg/m³ and average emissions of CO, NO_x and SO₂ for burning round bales 2210, 40.4 and 3.7 mg/m³. It is interesting that changes in nitrogen oxides were correlated with changes in oxygen content (**Figure 4**) [13].

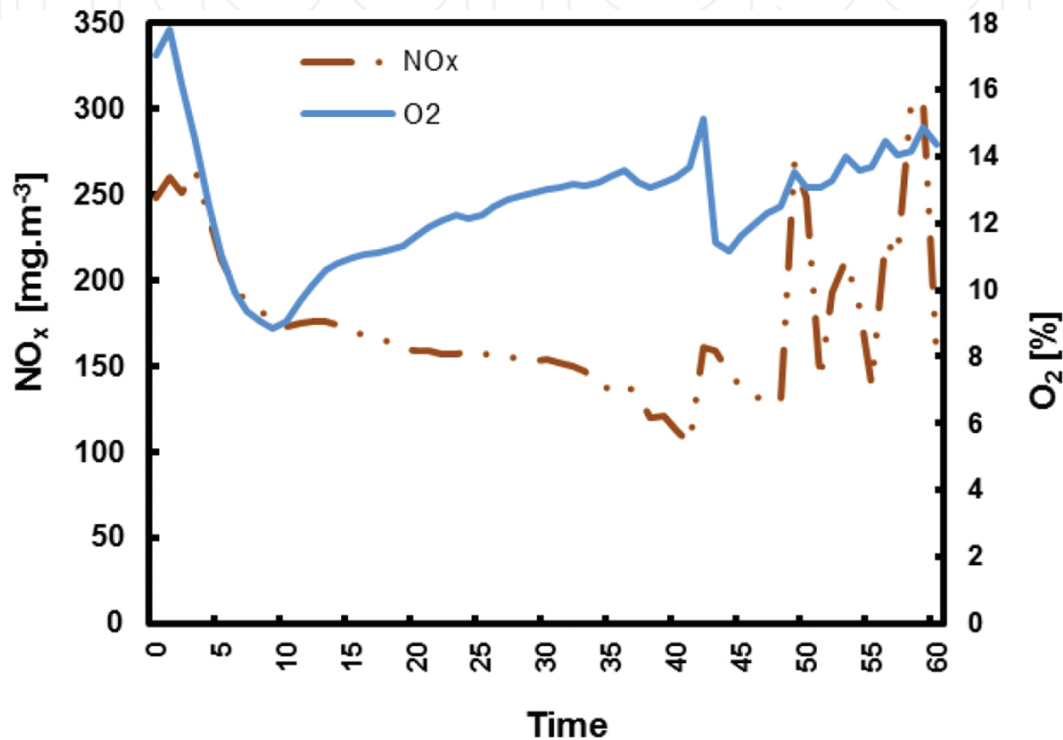


Figure 4. Trend in the emission of NO_x and O₂ during combustion of wood briquettes.

As emerged from these results, an acceptable solution could be more frequent feeding of a smaller fuel quantity at shorter intervals. This was confirmed by consequent analysis of the causes of dark smoke formation in the gasifying boiler with a nominal output of 99 kW. An experimental laboratory investigation was carried out to study the NO_x formation and reduction by primary measures for five types of biomass (straw, peat, sewage sludge, forest residues/Grot and wood pellets) and their mixtures in the work [21]. They found that NO_x emission levels were very sensitive to the primary excess air ratio and an optimum value for primary excess air ratio was seen at about 0.9. Conversion of fuel nitrogen to NO_x showed great dependency on the initial fuel-N content, where the blend with the highest nitrogen content had lowest conversion rate.

The gasifying boiler 2 with a nominal output of 99 kW often produced dark smoke. A demand was made to elaborate a proposal of technical-organisational measures for at least partial elimination of this negative aspect of power-producing use of piece rests of dry native wood

residues with lengths of up to 0.75 m from the furniture production. The boiler was expected to fulfil a single emission limit smoke darkness. The boiler operator was asked to periodically load fuel to the combustion chamber, to check temperature and pressure in the heat exchanger and to clean the device periodically. However, the regularity of feeding fuel from the viewpoint of emission minimisation was unknown. It was likewise unknown what the impact on concentrations of contaminating substances would have been for feeding dry, moist or even wet wood. The analysis of the time behaviour of emission creation on the basis of quite simple measurement of smoke darkness with proposed changes in feeding indicated possibilities for solving the problem of dark smoke creation (Figure 5).

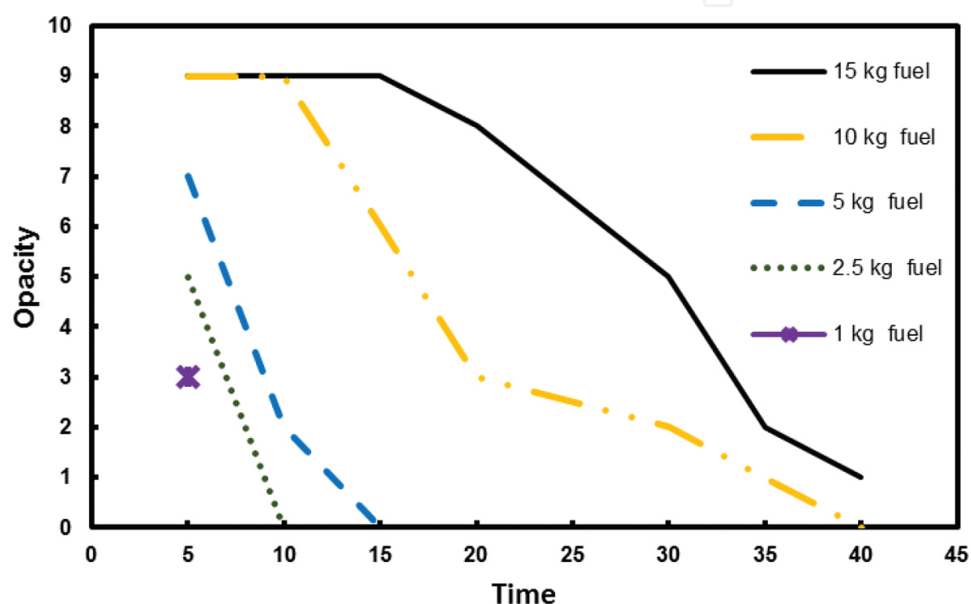


Figure 5. Trends in time behaviour of smoke darkness (opacity in the Bacharach scale) development from time of feeding of dry native wood residues with lengths of up to 0.75 m in the gasifying boiler.

By virtue of monitoring burning velocity, it can be said that this process is extremely rapid and thus highly susceptible to the formation of emission maxima. However, only dry native wood residues with lengths of up to 0.75 m are formed in operation. The combustion without emission maxima is for this reason possible only upon precise, uniform feeding at short time intervals.

The adaptation of an original one-stage combustion device with an output of 3.3 t/h of steam to a two-stage combustion device (boiler 3) did not bring an expected reduction in emissions when combusting dry fuel. In the first phase, after feeding beech and pine waste lumber and cuttings after drying into the boiler, black smoke originates even at sufficient oxygen concentration of 11.6%. During this phase, the CO concentration was approximately 30,000 mg/m³, TOC was approximately 1300 mg/m³ and NO_x was approximately 92 mg/m³. Dry wood burns quite rapidly after feeding and after black smoke appeared for several minutes with extremely high CO and TOC concentrations. These are products of wood tar and non-oxidised carbon.

When combusting boards bound by UF resin, a slower burning and a smaller emission extreme are visible in comparison with combustion of beech and pine waste lumber and cuttings after drying. After combustion of large-surface waste of particleboards bound by UF resin, no production of dark smoke was observed. When combusting large-surface material (waste of particleboards bound by UF resin) with lamination coating on the basis of melamine–urea–formaldehyde resin, the entire burning process took place in a steady phase; this is seen from the course of CO and TOC concentrations (**Table 1**).

Time from fueling (min)	Oxygen content (%)	Concentration (mg/m ³)		
		CO	TOC	NO _x
0–2	10.9	331	7	248
2–6	11.1	342	<5	234
6–10	11.9	292	<5	273
10–14	13.7	59	<5	316
14–18	12.4	263	9	271
18–20	15.3	28	14	312

Table 1. Concentrations of contaminating substances recalculated to oxygen content in waste gases of 11% from the combustion of particleboards with lamination coating on the basis of melamine–urea–formaldehyde resin.

N.M.	T _{fuel gas} (°C)	Output (%)	Oxygen content (%)	Concentration (mg/m ³)		
				CO	TOC	NO _x
1	145	60–63	15.34	2312	524	811
2	120	60–65	17.98	3626	781	925
3	132	65–70	17.00	2147	608	1017
4	130	70–75	18.91	4606	354	896
5	131	65–70	18.52	3301	263	985
6	135	70–75	17.49	2598	162	864
7	134	75–80	18.96	6744	298	821
8	136	8081	18.72	3852	251	923

Table 2. Summary of measured average half-hour emission values under conditions set as a standard with primary and secondary combustion air from boiler 4.

In small furniture shops, the interest in using their own waste, such as particleboards (PB), fibreboards (FB), or shaped pressed parts, for producing power has been increasing. However, securing conformity with the legal demands for air quality control is questionable. The study

of the thermo-degradation processes of adhesives and preservatives has led to useful results [22–24]. Information on thermodegradation of particleboards impregnated with various adhesives has been previously published in the works [25–27]. Our previous experiments under operational conditions showed that the impact of different binders in waste wood on CO emissions was slightly significant [4]. A similar result was obtained under laboratory conditions [26]. From a comprehensive analysis of results, it is clear that the thermal data and calorific value of biomass and biomass waste, in particular industrial wood waste, cannot be used as a basis for a regulation of the combustion process with the aim of minimising emissions.

The above-mentioned analysis results were also confirmed when examining the impacts of operational parameters of the automated warm-water boiler 4 on the concentrations of contaminating substances in waste gases. The results of the measurement of emissions under conditions of boiler operation set as a standard are given in **Table 2**.

We then optimised boiler operation precisely for the given kind of fuel. Results of emission measurements after the optimisation at the boiler output of 100% are given in **Table 3**.

N.M.	$T_{\text{fuel gas}}$ (°C)	Output (%)	Oxygen content (%)	Concentration (mg/m ³)		
				CO	TOC	NO _x
1	152	100	9.22	123	13	521
2	156	100	10.40	133	13	556
3	158	100	10.16	126	12	521
Stability control: average values						
4-8	159	100	9.81	97	11	508

Table 3. Summary of measured average half-hour emission values after optimisation of boiler 4's operation.

All of the results of emission measurement analyses under operational conditions show that waste combustion of particleboards in smaller wood boilers can also be optimised in such a way that the demands of emission limits are met. It arises hereafter from these results that modelling results for combustion emissions of industrial waste wood cannot be realised at the same level as they are for optimal combustion of natural, pure wood [28].

Tables 4–7 show the results of different operation regimes and **Tables 8–10** show different wood waste on two-stage combustion equipment—boiler 5. In **Tables 4–10**, the humidity means relative humidity, and harmful substances concentrations represent values calculated at 11% oxygen content in flue gas. The measured values mean the averages of at least three half-hour averages of measured concentrations.

The emission characteristics of the two-stage combustion equipment in an automated operation **Table 4** shows that even the commonly available two-stage combustion equipment is not able to keep the concentrations of harmful substances within the emission limits, which is proven by the exceeding of the emission limits $\text{CO} = 850 \text{ mg/mn}^3$.

Parameter	Unit	Measured value
Furnace type	Two-stage—pyrolysis pre-furnace	
Nominal power	0.6 MW	
Operation regime	Automated	
Fuel type	Wood chips (spruce)	
Humidity	%	40
Fuel consumption	kg/h	192
Flue gas		
Temperature	°C	199
O ₂	%	12.8
Flue gas volume	mn ³ /h	1432
Emissions (at O _r = 11%): average values		
TZL	mg/mn ³	*
CO	mg/mn ³	1093
NO _x	mg/mn ³	366

Notes: *Up to 60 mg/mn³ also in experiments with another material, thus they are not stated in further tables.

Table 4. Emission characteristics of two-stage combustion equipment in an automated operation regime: boiler 5.

In further experiments with wood and wood waste combustion, increased attention is paid to the operation of combustion equipment in a dynamic (not stable) regime. Dynamic states in operation of the combustion equipment are caused by a discontinuous dosing, or by continuous but not steady fuel dosing as well as by the regulation of incoming air. Emission characteristics measurements of the combustion equipment in a dynamic operation state were decided purposely due to the fluctuating heat take off from combustion equipment. The necessity to monitor the emission characteristics during dynamic operation of the combustion equipment is caused also by the fact that the majority of the fuel combustion processes is the power regulation. The fuel and air dosing is within the power regulation derived from the parameters of the heat transfer medium and its production.

Even the two-stage combustion equipment is not able to eliminate the unsteadiness of fuel dosing. At the jump change of the dosing (loading of the furnace with the fuel), the oxidation conditions of organic gaseous substances and carbon monoxide become worse. After loading the fuel, CO concentration immediately grows rapidly (**Table 5**). At the same time, conditions for decreased conversion of fuel nitrogen into nitrogen oxides [29] and low concentrations of nitrogen oxides are created. Probably the second stage of the combustion in this type of equipment does not meet all the construction requirements in order to achieve a high level of oxidation of organic gaseous substances. According to our calculations, this fact is caused by low temperature in the combustion chamber at the second stage (cooled by the boiler) and because flue gas remains in the chamber for a short time period.

Parameter	Unit	Measured value
Furnace type	Two-stage—pyrolysis pre-furnace	
Nominal power	0.6 MW	
Operation regime	Manual dosing—once completely filled reservoir above the grate	
Fuel type	Wood chips (spruce)	
Humidity	%	49
Fuel consumption	kg/h	204
Flue gas		
Temperature	°C	223
O ₂	%	13.7
Flue gas volume	mn ³ /h	1486
Emissions (at O_r = 11%)—average values at the time after fuel dosing*		
CO	mg/mn ³	27,981
NO _x	mg/mn ³	181

Notes: *In initial phase after the fuel metering were measured max. values of CO.

Table 5. Emission characteristics of two-stage combustion equipment when burning wood chips (spruce) and manual dosage in the initial phase of the fuel dosing: boiler 5.

Parameter	Unit	Measured value
Furnace type	Two-stage—pyrolysis pre-furnace	
Nominal power	0.6 MW	
Operation regime	Manual dosing—once completely filled reservoir above the grate	
Fuel type	Wood chips (spruce)	
Humidity	%	49
Fuel consumption	kg/h	204
Flue gas		
Temperature	°C	210
O ₂	%	18.3
Flue gas volume	mn ³ /h	1486
Emissions (at O_r = 11%)—average values at the time after fuel dosing *		
CO	mg/mn ³	480
NO _x	mg/mn ³	257

Notes: *In the phase before the burn out were measured min. values of CO.

Table 6. Emission characteristics of the two-stage combustion equipment when burning wood chips (spruce) and manual dosing in the phase before fuel burning out: boiler 5.

In manual fuel dosing, the last phase before the next dosing is the burn out phase. In this short phase, there is only the pyrolytic carbon and ashes in the primary combustion chamber. No gaseous organic substances are formed and CO concentrations are on the lowest level (Table 6).

In Table 7, average values are listed for the operation parameters and emissions during the whole fuel burning process under manual dosing—from loading until the end of continuous burning (up to 18% oxygen content in flue gas), immediately before the next fuel dose. When comparing the results of carbon monoxide and nitrogen oxides emissions measurements during the automated regime (Table 4) and manual regime (Table 7), it is evident that CO concentrations are at a higher level with manual dosing, and on the other hand, NO_x concentrations are higher with automated dosing. The automated dosing regime is stable without emission extremes of carbon monoxide concentrations. With manual fuel dosing, there are phases with high concentrations and low production of nitrogen oxides.

Parameter	Unit	Measured value
Furnace type	Two-stage—pyrolysis pre-furnace	
Nominal power	0.6 MW	
Operation regime	Manual dosing—once completely filled reservoir above the grate	
Fuel type	Wood chips (spruce)	
Humidity	%	49
Fuel consumption	kg/h	204
Flue gas		
Temperature	°C	218
O ₂	%	11.6
Flue gas volume	mn ³ /h	1486
Emissions (at O _r = 11%)—average values at the time after fuel dosing*		
CO	mg/mn ³	3537
NO _x	mg/mn ³	248
Phenol	mg/mn ³	6.4*
Formaldehyde	mg/mn ³	15*

Notes: *Average for the whole phase from dosage to the end of steady burning.

Table 7. Emission characteristics of the two-stage combustion equipment when burning wood chips (spruce) and manual dosing during the whole fuel burning phase: boiler 5.

In this boiler, very good results of CO concentrations were reached when burning spruce bark with steady manual dosing (Table 8). Higher nitrogen content in spruce bark ($N^{\text{daf}} = 0.38\%$) in comparison to spruce wood ($N^{\text{daf}} = 0.04\%$) was manifested in higher NO_x concentrations.

Parameter	Unit	Measured value
Furnace type	Two-stage—pyrolysis pre-furnace	
Nominal power	0.6 MW	
Operation regime	Steady manual dosing*	
Fuel type	Spruce bark	
Humidity	%	35
Fuel consumption	kg/h	100
Flue gas		
Temperature	°C	211
O ₂	%	12.0
Flue gas volume	mn ³ /h	1491
Emissions (at O _r = 11%)—average values in the steady combustion phase		
CO	mg/mn ³	202
NO _x	mg/mn ³	397

Notes: *In amounts approx. 15 kg each 9 min.

Table 8. Emission characteristics of the two-stage combustion equipment when burning spruce bark and steady manual dosing: boiler 5.

Parameter	Unit	Measured value
Furnace type	Two-stage—pyrolysis pre-furnace	
Nominal power	0.6 MW	
Operation regime	Steady manual dosing*	
Fuel type	Remains from PF plywood	
Humidity	%	8
Fuel consumption	kg/h	180
Flue gas		
Temperature	°C	224
O ₂	%	10.4
Flue gas volume	mn ³ /h	1468
Emissions (at O _r = 11%)—average values in the steady combustion phase		
CO	mg/mn ³	11
NO _x	mg/mn ³	382

Notes: *In amounts approx. 36 kg each 13 min.

Table 9. Emission characteristics of the two-stage combustion equipment when burning remains from PF plywood and steady manual dosing: boiler 5.

In **Tables 9** and **10**, CO and NO_x concentrations are listed in flue gas from waste combustion — waste from the plywood on a phenol–formaldehyde resin basis and chipwood boards on a urea formaldehyde resin basis. In both cases, low CO concentrations in flue gas were measured, which is caused by high calorific value of dry remains. The UF resin significantly increases the nitrogen content in fuel, which results in high values for NO_x concentrations.

Parameter	Unit	Measured value
Furnace type	Two-stage—pyrolysis pre-furnace	
Nominal power	0.6 MW	
Operation regime	Steady manual dosing*	
Fuel type	Remains from UF DTD	
Humidity	%	7
Fuel consumption	kg/h	140
Flue gas		
Temperature	°C	225
O ₂	%	10.8
Flue gas volume	mn ³ /h	1426
Emissions (at O _r = 11%)—average values in the steady combustion phase		
CO	mg/mn ³	81
NO _x	mg/mn ³	1260

Notes: *In amounts of approx. 23 kg each 10 min.

Table 10. Emission characteristics of the two-stage combustion equipment when burning UF DTD remains and steady manual dosing: boiler 5.

Boiler no.	Boiler 5 two-stage 0,6 MW	Boiler 6 two-stage 4,1 MW
Ratio of the waste from chipwood board (%)	35	50
Content of O ₂ (%)	14.3	13.3
CO (mg/mn ³)	172	88
NO _x (mg/mn ³)	588	503

Table 11. The results of measurements of pollutant emissions (as averages of three half-hour values calculated for 11% O₂) in flue gas from wood waste from furniture production.

Another goal of the emission limits measurements — when burning native wood and furniture residues from chipwood boards and MDF in boilers 5 and 6 — was setting the highest possible ratio of this waste in order to keep to the emission limits. The results of our measurements

(**Table 11**) show that the combustion process itself is highly efficient and there are no problems to keep to the CO emission limits. In boiler 5, it is possible to keep to the emission limit for NO_x with a ratio of the chipwood board in fuel up to 35%. In boiler 6, the emission limit for NO_x 650 mg/mn³ is maintained with a reserve with a ratio of chipwood board in fuel up to 50%.

In the past, extensive research was conducted on emissions from various combustion plants for wood and wood waste [4]. The set of emission measurements is from 31 types of combustion plants (prevailing output range of 20 kW–10 MW and combustion plants of standard and lower technical level) and 23 types of wood fuel and industrial wood wastes.

In order to evaluate a large number of emission measurement, we used the statistical method rotation in factor analysis. Varimax rotation is a useful statistical method used to simplify and better interpret the measuring results. We can identify and describe each variable with a single factor. The results of calculated varimax rotated factor matrix (**Table 12**) enable to identify the influence of combustion conditions on the production of CO, TOC and NO_x.

From the results of cited emission measurements, the factor analysis (**Table 12**) confirms the importance of precise oxide dosing (O₂) in the combustion space (variable/factor 1) for hydrocarbon emissions (C_xH_y) and carbon monoxide (CO). On the other hand, a type of wood fuel does not influence this factor of “good burning” (when respecting suitability for the given combustion plant). With important differences in oxygen content in industrial wood fuels, it is an influence of a kind of fuel (variable/factor 2) which is very important for producing nitrogen oxides (NO_x). At the same time, in the wide spectrum of analysed data, the variable/factor 2 confirms different and mutually opposing mechanism of producing pollutants of CO, TOC and NO_x.

Varimax rotated factor matrix		
Variable/factor	1	2
CO	0.6744	−0.5340
NO _x	0.1577	0.8720
TOC	0.8365	0.1244
O ₂	0.8395	−0.1660
Type of combustion plant	0.3858	−0.3569
Fuel sort	0.0166	0.8374

Table 12. Factor matrix of the results of measurements on the emissions from burning wood and wood wastes in various combustion plants.

This research shows further ways and means towards the realisation of measures to minimise emissions from the combustion of wood and wood waste. From the viewpoint of emission production, the decisive prevailing influence of the technique of wood waste combustion was proven in comparison with the influence of the chemical composition of wood waste. The knowledge and respecting the mechanism of producing pollutants are usable for regulation

of emissions from atypical combustion plants or generally for minimisation of emissions in combustion plants.

4. Case study: example of minimisation of emissions by appropriate boiler regulation

Emissions of individual pollutants at combustion of solid fossil fuels (black coal and lignite) and of biomass (wood pellets) in boilers can be found by the analyses of data obtained from different experiments or commercial measurements of emissions. Data for individual pollutants are described, for example, in the study [14] which summarises the most important findings concerning the production of pollutants at combustion of various fuels.

It is possible to see from the measurement results that combustion of biomass does not always directly reduce the amount of harmful emissions generated. An important factor is particularly the manner of combustion control, which is given by the method of fuel supply, simply speaking by stoking. The next section shows the method of regulation and of other modifications of the boiler MA 23, which resulted in reduction of emissions.

4.1. Comparison of the measured evolutions with expected ones

Stoichiometric analysis of fuel samples under normal conditions, and of reference oxygen content in the flue gas $O_r = 11\%$ corresponded to the excess air in the flue gas of $n = 2.1$. The values of thermal emission measurement in **Table 13** contain stoichiometric calculations, as well as the average values of measurements expressed as percentage of wet flue gas.

Volumetric combustion		Unit	MA23	PU25
Oxygen for combustion	O_{\min}	mn ³ /kg	0.815	0.906
Theor. air, dry	O_{air}^S	mn ³ /kg	3.881	4.313
Excess air	n	–	4.464	2.220
Water in flue gas	$V_{\text{H}_2\text{O}}^{\text{SP}}$	mn ³ /kg	0.794	0.744
Real flue gas, dry	$V_{\text{real, S}}^{\text{SP}}$	mn ³ /kg	17.286	9.537
Real flue gas, wet	$V_{\text{real V}}^{\text{SP}}$	mn ³ /kg	18.08	10.282
Nitrogen oxides	NO _x	% V/V	75.756	73.724
Carbon dioxide at $n = 1$	CO _{2max}	% V/V	16.515	16.97
Measured carbon dioxide	CO ₂	% V/V	4.28	8.271
Oxygen	O ₂	% V/V	15.8	10.765
Carbon monoxide	CO	% V/V	3.815	10.219
Water vapour	H ₂ O	% V/V	4.394	7.239

Table 13. Stoichiometric parameters.

It is evident from the results that increased oxygen content in the flue gas increases the CO content, that is, the component, from which it is still possible to extract some heat and to reduce thus the loss of the unused fuel. This observation leads us to the fact that gas did not get enough time to react with oxygen and to transform to CO₂.

Table 13 gives the percentage composition of real wet flue gas, when it is apparent that the percentage composition of the flue gas is affected also by the amount of flue gas. **Table 13** gives for comparison also the theoretical volume concentration of carbon dioxide at stoichiometric combustion, that is, with excess air $n = 1$. This is the maximum value of the carbon dioxide for a perfect transformation of carbon in the fuel, that is, an ideal state.

4.2. Analysis of hot water boiler MA 23

The boiler works on the principle of fuel gasification. It consists of two chambers situated one above the other. The upper chamber serves as a fuel reservoir with pre-burning, while the lower chamber serves as a combustion chamber and an ash pan, which allows perfect gasification of coal and wood. The bottom of the combustion chamber contains an afterburner chamber in which the wood gas and solid residues are burned. Supply of combustion air is realised by radial fan.

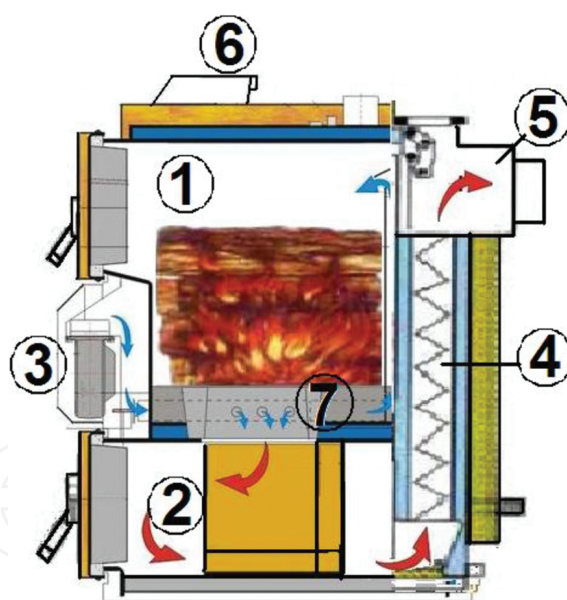


Figure 6. Hot water boiler MA 23—1. Stoking chamber, 2. Combustion chamber, 3. Fan, 4. Tube heat exchanger, 5. Chimney spout, 6. Electronic regulator, 7. Nozzle made of refractory concrete.

The boiler (**Figure 6**) provides a fuel pre-drying with subsequent gasification at higher temperatures. The primary air and secondary air are pre-heated and distributed in an ideal proportion to the centre of a fire and to the nozzle. The primary air is driven into the combustion chamber below the level of the upper door. Uniform distribution of pre-heated primary air ensures that the fuel gasification takes place gradually in small amounts of fuel. The boiler is

therefore economical and it has high combustion efficiency of 70–89% in the entire range of its power output. This arrangement allows better gasification of larger pieces of wood. The secondary air, which is fed to the gasification nozzle, is pre-heated to a higher temperature. The flame thus does not cool down and combustibles burn up completely. The lower combustion chamber is lined with refractory concrete in which the final burning of all solid particles, which fall down, takes place.

Figure 7(a) shows the original shaped piece through which the combustion air for secondary combustion was supplied by two large holes. **Figure 7(b)** shows the proposed shaped piece, which was also tested, through which the air was supplied along the longer side of the shaped piece by several holes. This resulted in a better reaction with the generated wood gas, in better burnout of gas and thus in the already mentioned reduction of emissions.

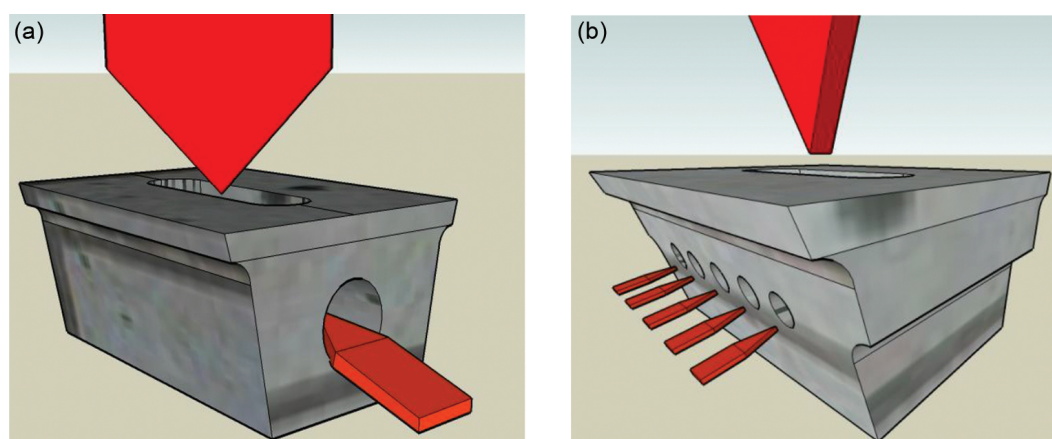


Figure 7. (a) Original shaped piece and (b) newly designed shaped piece.

Modification of combustion leads to reduction in generation of the gases we measured. The components of the produced gas have the ability to react with the incoming air to produce heat. Recording of the measured production of CO during the first test measurement (**Figure 7(a)**) of the rated heat output of the gasification boiler showed unsatisfactory results. Average value of carbon monoxide during two fuel charges without modification of the distribution of the combustion air, that is, with the initial fitting, was 2350 mg/m^3 . The gasification boiler, therefore, had to undergo a modification of the combustion air and gas inlet into the space of the secondary combustion zone; this position is in **Figure 6** indicated by number 2. This newly designed fitting does not have one hole of larger diameter but five holes along the longer side for the supply of secondary combustion air and gas from the gasification chamber (see **Figure 7(b)**). Modification of combustion leads to lower productions of the gases we measured. Modification of the fitting affected the measured values of carbon monoxide, which were on an average of 830.3 mg/m^3 . Such a result was expected and it was confirmed by measurements. The cause of this improvement consists in more even and planar supply of air. The air thus oxidises the active zone of the heating chamber in a wider area and greater volume. This brings a higher intensity of oxidisation and higher quality of combustion.

4.3. Verification and interpretation of the data obtained from the gasification boiler

Basic measurements by both direct and indirect methods were performed in accordance with the relevant standards and regulations for Slovak Republic, the Czech Republic and the EU. In the entire range from ignition to extinction (due to the need to compare modifications of equipment), we selected evaluation within the limits of water heated to 60°C up to 90°C, that is, within the temperature interval of the most frequently used operation. Our interest was to determine during this measurement the amount of CO (non-reacted fuel component) in dependence on the boiler output. We were also interested in the output water temperature in dependence on the flue gas temperature.

Average scatter is low due to the leap type control of the combustion air supply, when large fluctuations from the mean value are caused by the opening and closing of the air valves. **Table 14** presents the average values of the desired variables.

		Original state	New formed piece 1D	New formed piece 2D
P_{kot}	kW	19.2	19.3	18.5
CO	mg/m ³	2072.0	660.8	696.3
O ₂	%	16.6	16.5	18.2
NO _x	mg/m ³	115.2	120.4	90.9
Output temperature	°C	79.6	79.3	79.4
Chimney temperature	°C	154.3	156.6	145.9
Temperature gradient	°C	17.2	17.3	16.6

Table 14. Average values of the desired variables.

Measurement of performance parameters of the hot-water boiler MA 23 was performed by erudite experts from the Department of Energy Technology, Zilina University (ZU) in Zilina, Slovak Republic. They made measurements of all the parameters cited in the paper. The records of the tests were prepared both in tabular form and in diagrams. The measurement was performed continuously beginning from the first ignition of the boiler. The total duration of measurement was 405 min with steps of 1 min. The records were evaluated by regression analysis of the measured values. The correlation coefficient for all dependencies varies from 0.9 to 0.95. On the basis of the derived regression relationship, it is possible to render flow diagrams of the main functions, such as an increase in boiler output in kilo Watt, as shown in **Figure 8**. Optimal values functions are represented on the line of optimal performance, that is, 23 kW. In **Figure 8**, the functions are extended up to the output of 90 kW for more efficient boilers. Evolution of functions can be equally well plotted in dependence on time in minutes. **Figure 8** shows very clearly that combustion occurring during the first few minutes after ignition is rather problematic and unstable until an output of at least 10 kW is achieved. Evolutions of functions are interdependent, and we used them for the proposal of regulation of the combustion quality and oxygen balance by the ventilator. The sensor for continuous

measurement of temperature is situated in the stack throat. The regulator controls in dependence on the flue gas temperatures and fluctuations of the draught in the revolutions of an auxiliary fan. The coefficient of progression is defined as a dimensionless ratio between an optimal oxygen balance and the real one in relation to the optimal boiler output and to the corresponding desired oxygen balance according to the fuel.

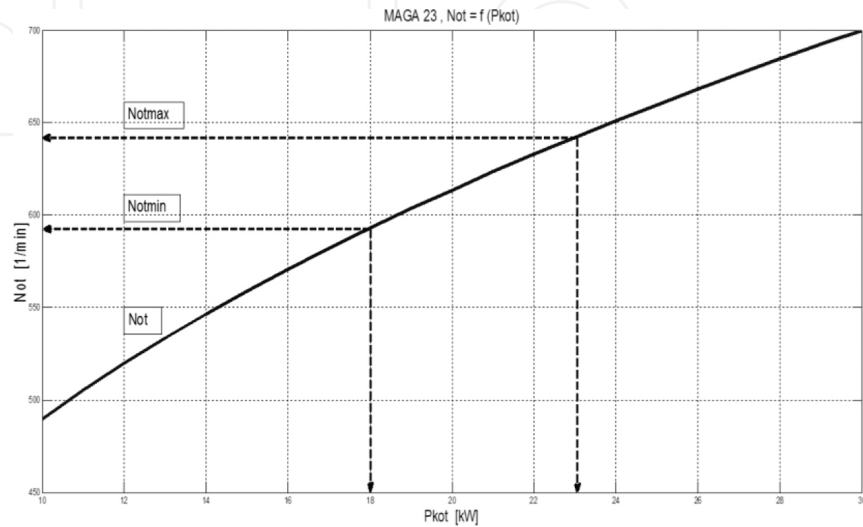


Figure 8. MA 23, fan revolutions in dependence on the power output.

A regression analysis was conducted on the basis of the data analysis in order to obtain description and prediction of the acquired dependencies and relationships between individual parameters. The analyses yielded in the following Eqs (1)–(12):

Dependence of draft in the chimney p_k on the power output P_{kot} :

$$p_k = 35.78498 + 2.0755 \cdot P_{kot} ; R^2 = 0.97 \quad (1)$$

Dependence of the chimney temperature t_k on the power output P_{ko} :

$$t_k = 124.14299 + 3.075308 \cdot P_{kot} ; R^2 = 0.93 \quad (2)$$

Progression coefficient of the oxygen balance K_{kb} to draft in the chimney p_k and optimal draft in the chimney p_{kOPT} :

$$K_{kb} = \frac{1.136 \cdot p_k}{p_{kOPT}} \quad (3)$$

Fan revolutions N_{ot} in relation to the power output P_{kot} :

$$N_{ot} = 10^{(2.265 + 0.325 \cdot \log(P_{kot}))} \quad (4)$$

Fan revolutions N_{ot} in dependence on the chimney temperature t_k :

$$N_{ot} = 10^{(2.265 + 0.325 \cdot \log(-1406.4927 + 49.81042 \cdot t_k - 0.69949 \cdot t_k^2 + 0.00494 \cdot t_k^3 - 1.75068 \cdot 10^{-5} \cdot t_k^4 + 2.49413 \cdot 10^{-8} \cdot t_k^5))} \quad (5)$$

Fan revolutions N_{ot} in dependence on the pressure in the chimney p_k :

$$N_{ot} = 10^{(2.365 + 0.325 \cdot \log(17.56402 + 0.4526 \cdot p_k))} \quad (6)$$

Values of emissions at the optimal power output (maximum power output) $P_{kotOPT} = P_{kotmax} = 23$ kW. In Eqs (7)–(12), the following is valid:

$$CO_{prep} = -2912.68649 + 698.44724 \cdot P_{kot} - 55.35295 \cdot P_{kot}^2 + 1.48709 \cdot P_{kot}^3 \quad (7)$$

$$NOx_{prep} = -361.15795 + 79.64852 \cdot P_{kot} - 5.70241 \cdot P_{kot}^2 + 0.14407 \cdot P_{kot}^3 \quad (8)$$

$$CO_{ppm} = -2351.95047 + 578.63494 \cdot P_{kot} - 46.84466 \cdot P_{kot}^2 + 1.27787 \cdot P_{kot}^3 \quad (9)$$

$$CO_{cmg} = -1782.53905 + 438.61597 \cdot P_{kot} - 35.51257 \cdot P_{kot}^2 + 0.96881 \cdot P_{kot}^3 \quad (10)$$

$$NOx_{ppm} = -77.93008 + 17.32183 \cdot P_{kot} - 1.24033 \cdot P_{kot}^2 + 0.03233 \cdot P_{kot}^3 \quad (11)$$

$$NO_{ppm} = 49.76939 - 10.47717 \cdot P_{kot} + 0.47193 \cdot P_{kot}^2 \quad (12)$$

The maximum output occurs at $P_{kot} = 23$ kW, see Eqs (1)–(6). These values were obtained from the operational measurements $p_k = 12.4475$, $t_k = 210.4638$, $K_{kb} = 1.136$, $N_{ot} = 642$.

It follows from Eqs (7)–(12) that the values of emissions were obtained in this manner:

$CO_{prep} = 1.9633 \cdot 10^{+003}$ (value standardised at the normal conditions), $NO_{xprep} = 207.0828$ (value standardised at the normal conditions), $CO_{ppm} = 1.7237 \cdot 10^{+003}$, $CO_{cmg} = 1.3070 \cdot 10^{+003}$, $NO_{xppm} = 57.6966$ and $NO_{ppm} = 58.4455$.

These values can be read on the straight line P_{kotmax} while maintaining the maximum output. The mechanism of the combustion process in the boiler can be actively controlled and regulated by fan revolutions. The boiler operates in such a way that temperature in the chimney is measured continuously and depending on it, the fan revolutions are regulated, for example,

with use of PID controller. The fan speed will be set according to **Figure 8** at 642 rpm. Control of revolutions, that is, of the chimney draft, is an important parameter that helps to stabilise a fluctuating combustion process.

Eqs. (1)–(12), derived by analytical processing of the measured values, are used in solution for conversion of the basic combustion functions to complex mathematical model of the combustion process as it is graphically represented in **Figure 8**. This mathematical model is of interactive nature, and it helps in programming of the electronic controller.

5. Conclusions

The results of emission measurement analyses indicated that the standard practice of boiler operation with a lower level on measurement and combustion process automation that governs the combustion mode on the basis of calorific value, humidity of wood fuel and demanded boiler output is insufficient for minimising emissions. For this reason, an original task for each type of boiler with wood as a fuel is to define optimum conditions of the combustion process under which the lowest emissions possible are reached.

New lessons from our operating experiments concerning the production of pollutants during power generating using wood and wood waste are useful for reducing emissions:

- from small combustion plants,
- from unconventional combustion plants and in general to minimise emissions from other biomass combustion plants.

The results of analyses showed that the standard mode of operation for a particular wood boiler, as a result of large variability of wood fuel and waste wood properties, should be optimised by virtue of emission measurements.

The analysis of time behaviour for wood boiler emissions is a good basis for a theoretical analysis examining the possibilities for adaptation of the usual mode of boiler operation with the aim of reducing emissions.

The results of combustion mode adaptation in six types of boilers with smaller outputs show by virtue of emission measurements and according to the methodology worked out that when combusting wood of various dimensions (briquettes, cuttings) or waste wood cuttings (of fibreboards and particleboards bound by UF resin, and/or with lamination coating on the basis of melamine-urea-formaldehyde resin), it is possible to markedly reduce emissions and smoke darkness.

The purpose of design of gasification boilers consists in the most effective and most perfect combustion of volatile substances (especially carbon monoxide) in the secondary combustion zone. Insufficient amount of combustion air in the combustion nozzle leads to high emissions of carbon monoxide.

After analysis of the results of emission measurements, we proposed a new component of the boiler, that is, the shaped piece between the gasification and post-combustion chamber. This

modification reduced the values of emissions, so combustion occurred with higher efficiency and the values of the generated flue gas CO, CO₂ and other components of the flue gas got stabilised. We also proposed control of the combustion air supply.

The next modification concerns the electronic control. The tested gasification hot water boiler is equipped with a reliable microprocessor controller of the type G-403-P02, which provides control of air supply via fan on the basis of the input temperatures, which ensures a relatively wide range of boiler regulation between 30 and 100% of the rated power output of the boiler, as well as its safe operation. Combustion is then closer to the ideal, stoichiometric combustion, which manifests itself by the smallest possible air excess. This condition ensures us low production of flue gas and thus also of the resulting pollutants.

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